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RESEARCH ARTICLE

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Ecoacoustics as a novel tool for assessing pond restoration success: Results of a pilot study

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Abstract

1. Ecoacoustics is increasingly being used to monitor species populations and to estimate biodiversity in marine ecosystems, but the underwater soundscapes of freshwater environments remain largely unexplored in this respect. Few studies exist concerning the acoustic diversity of ponds, but because aquatic plants and many arthropods such as Coleoptera and Hemiptera are known to produce sound, there is potential to use ecoacoustic techniques to monitor changes in biodiversity and conservation value.
2. This pilot study compares the underwater soundscapes of recently restored open-canopy ponds and unmanaged highly terrestrialized ponds situated in an arable agricultural landscape of North Norfolk, UK, in order to assess the benefits of farmland pond restoration.
3. Daytime sound recordings were made for 10 min in each pond and analysed primarily for arthropod stridulations. In addition, six commonly used acoustic indices were calculated to assess the soundscape biodiversity between the unmanaged and the restored ponds. The stridulations of three diving beetle species (Dytiscidae) were recorded in tank studies to assess the potential for individual species recognition from underwater sound capture.
4. Sound-type richness and abundance, as estimated by visually and aurally identifying arthropod stridulation from spectrograms, were significantly higher in the restored open-canopy ponds compared with the unmanaged terrestrialized ponds. In addition, the acoustic indices 'acoustic complexity' and 'biodiversity index' were significantly higher in restored open-canopy ponds than in unmanaged terrestrialized ponds.
5. The three dytiscid water beetle species recorded in a tank were found to produce distinctive and recognizable sounds, indicating potential to create an audio reference library that could be used for automatic acoustic monitoring of freshwater arthropods.
6. Pond soundscapes are rich in biological information and this study suggests that, with further development, automated passive ecoacoustic monitoring could be an effective non-invasive technique for assessing pond conservation value and pond restoration and management success.

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KEYWORDS

biodiversity estimation, Dytiscidae, freshwater conservation, stridulation, water beetle

1 | INTRODUCTION

Recording and documenting the sounds that species produce in an environment can be harnessed by researchers as a non-invasive survey technique, alongside traditional biodiversity surveys (Harris, Shears & Radford, 2016). Growing interest in recording all of the biological, geophysical, and anthropogenic sounds present in a location at any time (the soundscape) has recently led to the creation of the field of ecoacoustics (Sueur & Farina, 2015). Ecoacoustics uses acoustics to address biodiversity and ecological questions and is being increasingly used to monitor species populations and to estimate biodiversity (Sueur & Farina, 2015). For example, ecoacoustic approaches have been used to assess patterns of spatial biodiversity, and hence identify areas of conservation value, in forest plantations (Grant & Samways, 2016) and to monitor the recovery of an island seabird colony following the removal of an invasive predator (Borker, 2018). Although there have been many studies investigating the soundscapes of terrestrial (Blumstein et al., 2011; Scarpelli et al., 2020) and marine environments (Erbe, 2010; Pieretti et al., 2017), the soundscapes of freshwater environments remain largely unexplored (Linke et al., 2018). However, several recent studies on the acoustic diversity of temperate ponds and freshwater arthropods show the promise of soundscape-based approaches (Sueur, Mackie & Windmill, 2011; Greenhalgh et al., 2020).

Aiken (1985b) suggested that most acoustic diversity in ponds is generated by arthropod stridulation, a process that involves the physical interaction of two hard body parts. The ability to stridulate is known for at least four freshwater invertebrate orders: Trichoptera (caddisflies), Odonata (dragonflies), Heteroptera (true bugs), and Coleoptera (beetles) (Aiken, 1985b). However, Wilson et al. (2015) suggested that stridulation occurs most notably in the adult forms of the last two invertebrate orders. The sounds produced by Heteroptera (notably water boatmen) are perhaps the most studied (Jansson, 1968; Jansson, 1973; Theiss, 1983; Sueur, Mackie & Windmill, 2011). Water beetles are also known to produce sounds underwater and many are useful biological indicators of environmental change (Sánchez-Fernández et al., 2006; Wilson et al., 2015). Recently, an ecoacoustic approach has been adopted by many authors to survey freshwater ecosystems (Desjonquères et al., 2015; Barclay, Gifford & Linke, 2020; Decker et al., 2020; Karaconstantis et al., 2020; Linke, Gifford & Desjonquères, 2020; Rountree, Juanes & Bolgan, 2020). However, an ecoacoustic survey approach has not yet been used to assess diversity and conservation success in ponds.

Ponds are known to be in decline at a global scale, owing to a range of stressors including deliberate infilling, pollution, habitat fragmentation, invasive species, and the removal of natural pond

disturbance (Hill et al., 2018). In the UK, the majority of ponds are located in farmland and are frequently surrounded by intensive arable land, rendering them subject to eutrophication and other forms of pollution (Wood, Greenwood & Agnew, 2003). Furthermore, UK farmland ponds are widely threatened by terrestrialization, resulting in the overwhelming numerical dominance of late-successional ponds with high canopy shading and lowered species diversity at pond and pond-landscape scales (Sayer et al., 2013; Sayer & Greaves, 2020). To tackle the problem of terrestrialization, farmland ponds can be restored by active tree and sediment removal, and much recent research shows this approach to be highly effective (Sayer & Greaves, 2020; Walton et al., 2021).

This pilot study investigated the potential of ecoacoustic surveys for assessing the success of pond restoration. The management of highly terrestrialized ponds by scrub and sediment removal, and the resulting return of macrophyte-dominated conditions, has been shown to increase invertebrate diversity in UK farmland ponds (Sayer et al., 2012). Hence, we hypothesised that the soundscapes of restored, macrophyte-rich ponds would possess greater acoustic diversity than unmanaged, highly terrestrialized ponds. In addition, we hypothesized that different species of dytiscid water beetles would produce distinct sounds.

2 | METHODS

This pilot study focused on 10 small (<1,300 m²) and shallow (<1.6 m in depth) ponds situated in the villages of Bodham, Baconsthorpe, and Briston in North Norfolk, eastern England, UK (Table 1). The study ponds have their origins as marl pits and water sources for livestock (Sayer et al., 2013), and all pre-date maps from 1836, which show the ponds as present (Lewis-Phillips et al., 2019). All ponds are situated in a low-lying (<100 m a.s.l.) agricultural landscape dominated by free-draining loamy soils (Landis, 2018) interspersed with patches of deciduous woodland and grassland. The 10 study ponds were divided equally into two groups: (i) five 'terrestrialized unmanaged ponds', which had not been subjected to management for at least 30–40 years and, as a result, were highly shaded and largely free of macrophytes (Figure 1a); and (ii) five 'open-canopy managed ponds' that were macrophyte dominated, resulting from recent restoration or long-term scrub management (Figure 1b).

2.1 | Pond recordings

All sound recordings were made with an uncalibrated custom-made Jez Riley French hydrophone (standard) at a sample rate of 48 kHz, with 16-bit depth, in a .wav format onto a Tascam DR-70D (TASCAM,

TABLE 1 Time of recording, sound-type richness, and sound-type abundance for the 10 study ponds

Pond code	Latitude, Longitude	Pond size (m ²)	Max. water depth (cm)	Macrophyte cover (%)	Time of recording	Sound-type richness (per 10 min)	Sound-type abundance (per 10 min)
Open canopy, managed							
SABA	52.919501, 1.152350	400	160	95	10:23 AM	15	207
BECK	52.894833, 1.136436	300	100	95	11:15 AM	14	92
WADD9	52.844644, 1.040134	400	100	100	7:09 PM	18	265
WADD17	52.844090, 1.045671	1,250	130	80	5:53 PM	12	226
WADD23	52.861104, 1.054324	375	80	80	3:00 PM	13	120
Overgrown, unmanaged							
STODY9	52.867835, 1.030736	300	80	0	11:46 AM	6	23
STODY10	52.869286, 1.031975	225	100	0	12:15 PM	7	18
BAW02	52.900461, 1.163121	280	50	0	3:53 PM	1	1
NROAD	52.894465, 1.163108	300	70	0	5:16 PM	9	42
PYES5	52.843093, 1.050561	400	40	0	5:05 PM	4	11

**FIGURE 1** Overgrown unmanaged study pond (a) and open-canopy managed study pond (b)

Montebello, California, United States) with a Sound Devices Mix-Pre used as a mixer (Sound Devices, Madison, Wisconsin, United States). The hydrophone was submerged at least 20 cm below the surface,

next to the pond margin, and a 10-min recording was made after 3 min had elapsed, so that any noise from popping air bubbles escaping from disturbed silty sediment had largely ceased. All recordings were conducted between 10:00 AM and 7:00 PM from 20 to 24 June 2017. Ponds were sampled at random to reduce the influence of any effect produced by the time of day.

2.2 | Species recordings

Each pond was sampled with a long-handled standard pond net (mesh = 1 mm) for a 3-min period, divided proportionately among the major microhabitats present (Biggs et al., 1998). Captured water beetles were sub-sampled and left alone in a sorting tray. Water from the pond was then filtered through the pond net into a small tank (100 cm × 30 cm × 30 cm; Figure 2) to ensure that no other sound-producing organisms, other than the target species, were present in the tank water. A small net was suspended in the tank to act as a holding area for water beetles and to prevent unwanted sounds caused by collisions with the hydrophone. The hydrophone was inserted into the tank between the tank wall and the net, and a 3-min listening period ensured that no other sound-producing organisms were present. The field tank contained only one individual of a single species at any time. Each test water beetle was allowed to acclimatize for 5 min before a recording was made for an additional 5 min. If a sound was produced during the recording period, the test organism was transferred into a plastic container and preserved on site in 90% industrial methylated spirit for later species identification using the method described by Foster & Friday (2011) and Foster, Bilton & Friday (2014). The species recordings collected as a result of this study have been deposited in the sound archives of the British Library and BioAcoustica (Baker et al., 2015).

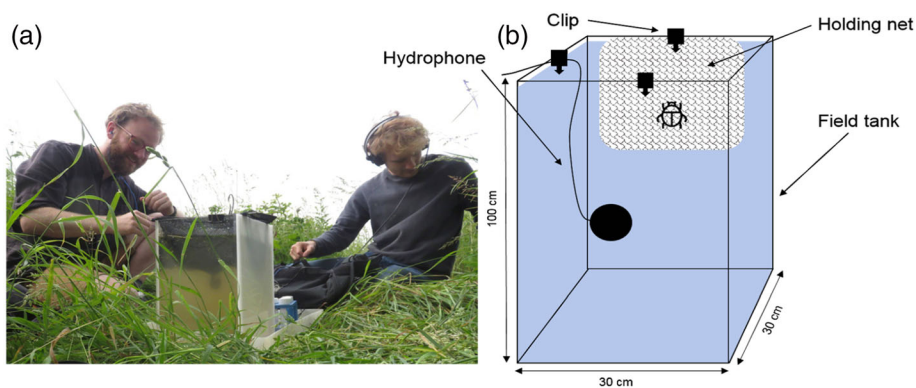


FIGURE 2 Tank set-up used for recordings of the lesser-diving water beetle *Acilius sulcatus*, the cherrystone water beetle *Hyphydrus ovatus*, and the supertramp water beetle *Rhantus suturalis*: (a) field tank in situ; (b) field tank schematic

2.3 | Audio processing and estimation of sound diversity

Audio files were downloaded from the Tascam onto a hard drive and imported into AUDACITY 2.1.3 (<https://www.audacityteam.org>), a free open-source audio editor. Parameters derived from the acoustic data collected were divided into two groups: (i) manual parameters derived from visual and aural inspection of spectrograms; and (ii) computational parameters derived from the calculation of acoustic indices.

Manual parameters were calculated by quantifying 'sound types': unique sounds identified both aurally and visually with the use of spectrograms generated in AUDACITY (spectral range, 0–24 kHz; spectrogram parameters, Fourier window length of 1024 samples; frame overlap, 0%; window type, Hanning), as also described by Desjonquères et al. (2015, 2018) and Gottesman et al. (2020). In order to increase the likelihood of the visual detection of aquatic insect stridulations in the spectrograms, noise reduction was conducted by selecting a section of audio consisting only of background noise, obtaining a noise profile by using the default settings in AUDACITY, and applying the noise profile of the background noise to the rest of the recording. In addition, a high-pass filter was applied to each recording at a frequency of 1000 Hz with a 12 dB per octave roll off. Sound types were identified and distinguished aurally based on audible differences and visually, based on their spectral signatures. Each sound type was then numbered, the corresponding audio file and spectrogram saved, and a reference library created. This process was repeated for all pond recordings and the reference library was double-checked for inaccuracies. Each pond recording ($n = 10$) was simultaneously listened to and observed (via the spectrogram) by one person (JG) in real time in AUDACITY. The number of sound types present in each pond recording was counted to determine the 'sound-type richness'. In addition, the number of occurrences of each sound type was counted to determine the 'sound-type abundance'.

Computational metrics, the acoustic complexity index (ACI) (Pieretti, Farina & Morri, 2011), the acoustic richness (AR) (Depraetere et al., 2012), the acoustic diversity index (ADI) (Villanueva-Rivera et al., 2011), the acoustic evenness index (AEI) (Villanueva-Rivera et al., 2011), the bioacoustic index (BI) (Boelman et al., 2007), and the normalized difference soundscape index (NDSI) (Kasten et al., 2012)

were calculated by applying default settings in RSTUDIO 1.2.1335 using raw, unedited .wav format audio files with the package SEEWAVE (Sueur, Aubin & Simonis, 2008).

The acoustic complexity index (ACI) measures the variation in amplitude between successive frames and then sums the values across frames and frequency bins. ACI is therefore sensitive to modulations in sound that are characteristic of many biological signals. AR ranks audio files based on their temporal entropy and amplitude. ADI is the Shannon index, which is calculated using the amplitude values of acoustic signals within frequency bins. AEI calculates a Gini index as a result of the proportion of acoustic signals within frequency bins. BI estimates the acoustic activity within the biophony (2–8 kHz), and NDSI estimates the level of human disturbance within the soundscape by calculating a ratio of anthrophony (1–2 kHz) to biophony (2–8 kHz).

2.4 | Statistical analysis

To determine whether the soundscapes of open-canopy restored ponds significantly differed from the soundscapes of unmanaged highly terrestrialized ponds, Welch's two-sample t-test (Welch, 1947) was calculated for sound-type richness and sound-type abundance, and for each acoustic index: ACI, AR, ADI, AEI, BI, and NDSI. Welch's t-test was deemed appropriate given the normally distributed nature and unequal variance of the data. A Pearson correlation was calculated to determine the degree of association between sound-type richness and sound-type abundance with each of the acoustic indices (Table 2). A Pearson correlation was selected because the data are continuous and possess both linearity and homoscedasticity.

In addition, to assess compositional variation between sound types and the two study pond categories, a non-metric multidimensional scaling (NMDS) was produced (distance = 'bray') using the package VEGAN in RSTUDIO (Oksanen et al., 2010). Sound-type richness and sound-type abundance data were log-transformed before performing the NMDS to account for sound types with a high abundance.

Audio files of three dytiscid water beetles (*Acilius sulcatus*, *Hyphydrus ovatus*, and *Rhantus suturalis*) that were recorded in the tank studies were imported into RSTUDIO, and the statistical characteristics of each beetle stridulation were calculated with the

package SEEWAVE (Sueur, Aubin & Simonis, 2008). Spectrograms of each species were then produced with a fast Fourier transform size of 700 (Hanning window). Further inspection of each water beetle spectrogram was undertaken in RAVEN, in which the cursor can be used to highlight points of interest on the spectrogram to return numerical values of time in seconds to three decimal places, frequency in Hz, and relative decibels to one decimal place.

3 | RESULTS

3.1 | Pond recordings

In total, 52 sound types (numbered hereafter) were identified from the 10 study ponds. Sound types 21, 31, 36, 45, and 48 were unique to the unmanaged highly terrestrialized ponds. Sound types 3, 8, 13, 16, 17, 34, 37, 44, 46, 47, 49, and 50 occurred in both the restored open-canopy and unmanaged ponds. The remaining 35 sound types were unique to the restored ponds. The most ubiquitous sound types (found in five or more ponds) were 13, 16, and 17 (Table 3). Welch's two-sample *t*-tests showed that restored ponds possess a significantly greater sound-type richness ($t = 4.9$, $P = 0.001$) and sound-type abundance ($t = 4.8$, $P = 0.006$) than unmanaged terrestrialized ponds, as displayed by box plots comparing the pond management types (Figure 3). Audio files and spectrograms of all 52 sound types described in this study can be found in Appendix S1.

3.2 | Acoustic indices

Welch's two sample *t*-tests showed that the values calculated for the indices ACI ($P \leq 0.00049$) and BI ($P \leq 0.0021$) were significantly higher for restored open-canopy ponds than for highly terrestrialized unmanaged ponds. The indices ADI ($P = 0.037$) and NDSI ($P = 0.011$) were significantly higher for unmanaged terrestrialized ponds than for managed open-canopy ponds, whereas the indices AR ($P = 0.202$) and AEI ($P = 0.073$) showed no significant difference between the two pond management types (Figure 4).

Pearson correlation showed that the indices ACI, AEI, and BI were positively correlated ($P \leq 0.05$) with both sound-type richness and sound-type abundance (Table 2). The indices ADI and NDSI were negatively correlated with sound-type richness and sound-type abundance. The Pearson correlation plots of each acoustic index as a function of sound-type richness and sound-type abundance can be found in Figures S2 and S3.

3.3 | Non-metric multidimensional scaling

The NMDS analysis of sound types and pond management types indicated that restored open-canopy and unmanaged terrestrialized pond sites differed substantially in terms of sound-type composition and sound-type abundance (Figure 5). The soundscapes of each pond also appeared to be relatively distinct from each other.

TABLE 2 Pearson correlations between the acoustic indices (acoustic complexity index, ACI; acoustic richness, AR; acoustic diversity index, ADI; acoustic evenness index, AEI; bioacoustic index, BI; and normalized difference soundscape index, NDSI) and sound-type richness and sound-type abundance

	ACI	AR	ADI	AEI	BI	NDSI
Richness	0.014*	0.320	0.013*	0.040*	0.015*	0.035*
Abundance	0.013*	0.610	0.036*	0.072	0.005**	0.016*

Note: Asterisks indicate the significance of the test:

* $P < 0.05$;

** $P < 0.01$.

TABLE 3 Sound type occurrence at the 10 study ponds

	Sound types
Managed open-canopy ponds	
SABA	1, 7, 8, 16, 19, 22, 25, 29, 32, 33, 35, 40, 47, 50, 52
BECK	3, 13, 15, 17, 18, 20, 23, 26, 34, 37, 42, 43, 44, 51
WADD9	1, 4, 5, 6, 9, 10, 11, 13, 15, 16, 17, 22, 26, 27, 32, 33, 37, 46
WADD17	3, 12, 14, 16, 24, 26, 32, 38, 39, 40, 49, 51
WADD23	2, 3, 13, 14, 16, 23, 25, 28, 30, 32, 40, 41, 49
Unmanaged terrestrialized ponds	
STODY9	17, 34, 44, 46, 47, 48
STODY10	13, 16, 17, 21, 36, 37, 44
BAWO2	13
NROAD	8, 13, 16, 17, 31, 34, 45, 49, 50
PYES5	3, 8, 13, 50

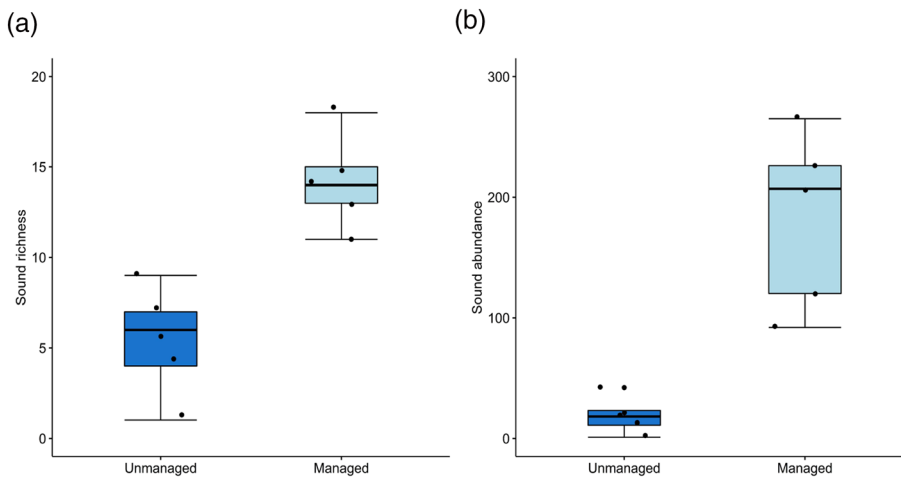


FIGURE 3 (a) Sound-type richness and (b) sound-type abundance comparison for the 10 study ponds. Lower whisker = 25% – 1.5 × the interquartile range; upper whisker = 75% + 1.5 × the interquartile range

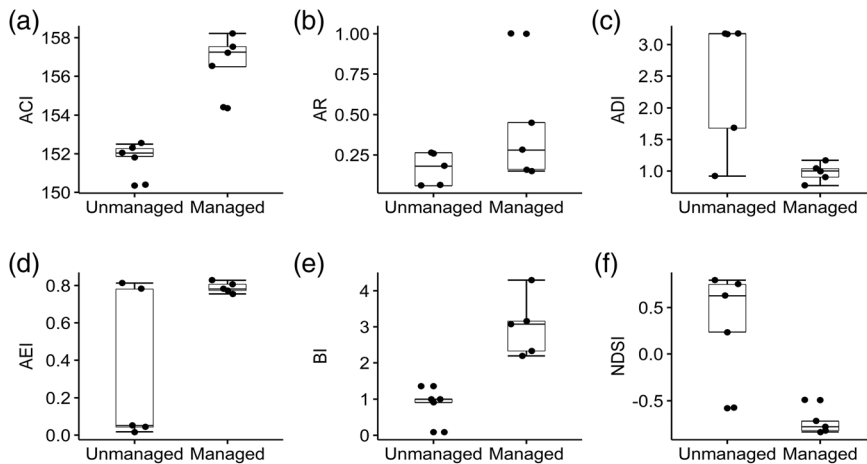


FIGURE 4 Acoustic index values for open-canopy managed ($n = 5$) and highly terrestrialized unmanaged ($n = 5$) ponds: (a) acoustic complexity index, ACI; (b) acoustic richness, AR; (c) acoustic diversity index, ADI; (d) acoustic evenness index, AEI; (e) bioacoustic index, BI; and (f) normalized difference soundscape index, NDSI. Lower whisker = 25% – 1.5 × the interquartile range; upper whisker = 75% + 1.5 × the interquartile range (* $P < 0.05$, ** $P < 0.01$)

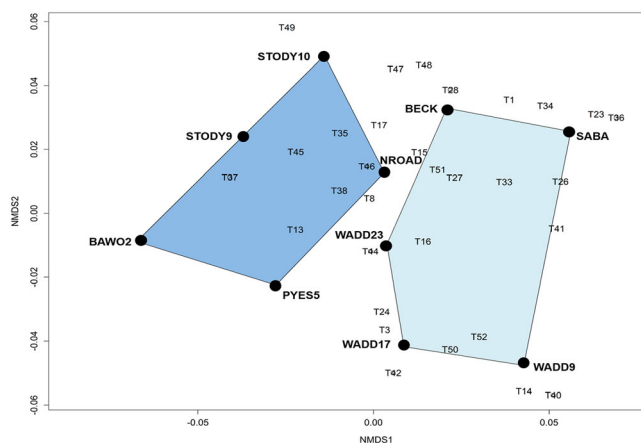


FIGURE 5 Non-metric multidimensional scaling plot showing pond sites (in bold) and sound types (see Table 2). Light-blue convex hull, open-canopy managed ponds; dark-blue convex hull, highly terrestrialized unmanaged ponds. Distance = 'bray'. The stress plot can be found in Figure S4

3.4 | Species recordings

3.4.1 | *Acilius sulcatus*

The signal produced by *A. sulcatus* ($n = 1$) was initiated with a pulse train of five clicks (frequency range: 2.6–11.8 kHz) (Figure 6). These were preceded by a 'humming' phase that began with lower-frequency stridulations (3–5 kHz), which decreased in intensity over a 16.3-s period. A further pulse train of 22 high-frequency pulses (8.1–11.6 kHz) was produced concurrently with the humming phase, lasting for the remainder of the recording (Table 4).

3.4.2 | *Hyphydrus ovatus*

Hyphydrus ovatus produced a signal ($n = 1$) consisting of high-frequency stridulations (5.2–12.5 kHz) for a period of 9.7 s (Figure 6).

FIGURE 6 Spectrograms of the lesser-diving beetle *Acilius sulcatus*, the cherrystone water beetle *Hyphydrus ovatus*, and the supertramp water beetle *Rhantus suturalis* recorded on site in a field tank, (see Figure 2). The duration of the spectrogram for each species is different

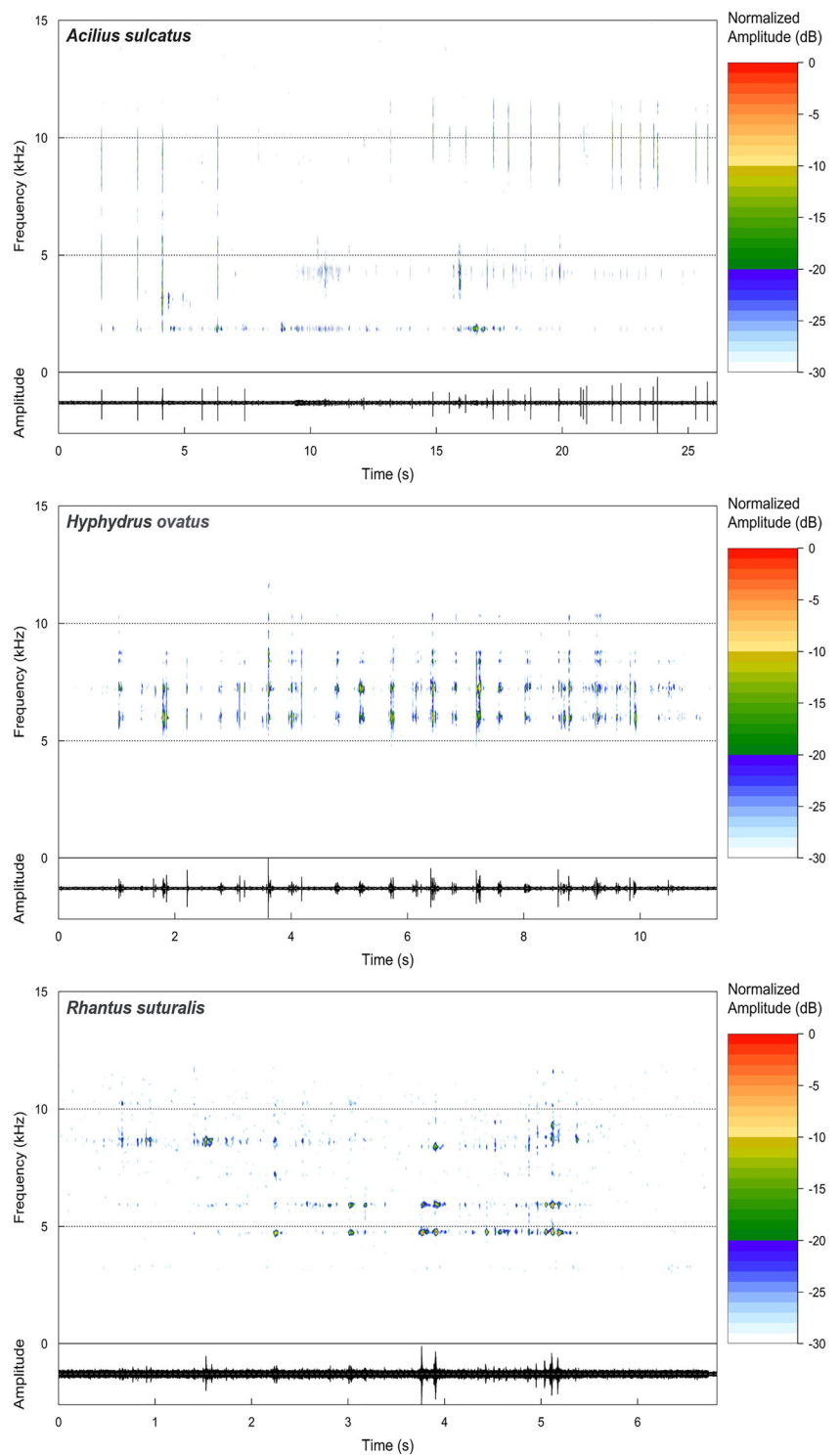


TABLE 4 Descriptive statistics of Coleoptera species recordings ($n = 1$) for the lesser-diving beetle *Acilius sulcatus*, the cherrystone water beetle *Hyphydrus ovatus*, and the supertramp water beetle *Rhantus suturalis*

Species	Dominant frequency (kHz)	Mean frequency (kHz)	Median frequency (kHz)	Duration (s)
<i>Acilius sulcatus</i>	1.88	6.83	6.87	26.14
<i>Hyphydrus ovatus</i>	7.22	9.22	8.37	11.32
<i>Rhantus suturalis</i>	8.62	7.68	7.71	6.84

Note: The dominant frequency describes the frequency with the highest amplitude.

The sound produced resembled that of metal ball bearings in an egg shaker.

3.4.3 | *Rhantus suturalis*

The signal produced by *R. suturalis* ($n = 1$) consisted of simultaneously occurring high-frequency (8.2–10.3 kHz) and low-frequency (4.3–6.0 kHz) bands (Figure 6). Interestingly, a frequency gap appeared between approximately 6.0 kHz and approximately 8.2 kHz during the recording, although a few signals were detected at approximately 7.1 kHz. A pause in the signal occurred at 3 s for 0.4 s, after which the initial signal was repeated. A potential additional frequency band was also detected at approximately 11.1 kHz.

4 | DISCUSSION

4.1 | Ecoacoustic monitoring of ponds

This study supports the suggestion that ecoacoustics may afford a useful and novel non-invasive tool for assessing the conservation value of ponds; in this case, for quantifying the biodiversity benefits of restoring farmland ponds to open-canopy, macrophyte-dominated conditions by scrub and sediment removal. The ecoacoustic data gathered in this study support previous work showing that open-canopy, macrophyte-dominated farmland ponds possess a higher diversity of water beetles (Coleoptera) and water bugs (Hemiptera) compared with unmanaged, highly terrestrialized ponds, where macrophytes are largely absent owing to heavy tree shading (Sayer et al., 2012). The open-canopy ponds were quite simply noisier, reflecting higher invertebrate diversity and activity. Furthermore, open-canopy ponds contained more sound types potentially produced by aquatic plant respiration (Linke et al., 2018).

Equally, in support of the view that invertebrate diversity at the landscape scale is maximized where ponds are at a range of successional stages (Collinson et al., 1995; Lundkvist, Landin & Milberg, 2001; Sayer et al., 2012), the NMDS analysis (Figure 5) showed a clear separation between the restored open-canopy and highly terrestrialized ponds, suggesting differing soundscapes and hence invertebrate and aquatic plant communities. The diversity of sound types described ($n = 52$) for the ponds reflects the high diversity of water beetles, bugs, and aquatic plants that occur in the 10 ponds studied. Acoustic diversity as measured in this study was probably the result of a combination of environmental and biological factors. Sueur, Mackie & Windmill (2011) showed that body size in the lesser water boatman *Micronecta scholtzi* was positively correlated with signal amplitude. When scaled to body length, *M. scholtzi* was capable of producing a sound with more energy than most terrestrial and marine mammals, and it was suggested that such loud stridulation was the result of runaway sexual selection of a courtship call. It follows that the overlap of the acoustic survey conducted in this study with the summer breeding season of many aquatic insect species might have resulted in

a greater number of courtship calls, and hence the high acoustic diversity observed. Environmental factors such as water temperature and light intensity are also known to influence the acoustic activity of aquatic insects, which may have resulted in varying acoustic diversity (Jansson, 1968; Aiken, 1985a). All of these factors are worthy of further investigation in future studies.

Acoustic niche partitioning, whereby vocal species adapt to mitigate competition by producing novel signals, is also a potential source of acoustic diversity (Krause, 1993). This was initially described in anuran communities and has been the subject of several studies (Littlejohn, 1965; Chek, Bogart & Loughheed, 2003; Steelman & Dorcas, 2010), being described along three dimensions: time, acoustic frequency, and space (Wells, 2007). However, interference or the overlapping of signals can pollute transmission and limit the chance of subsequent biological reward, such as a mating partner. To overcome broadcasting competition, it has been suggested that *M. scholtzi* produces a high-amplitude signal with the ability to drown out competition and travel long distances (Sueur, Mackie & Windmill, 2011). Another strategy consists of producing a short signal in a regularly repeating pattern, as observed in anurans, to ensure the transmission of information (Chek, Bogart & Loughheed, 2003). Such patterns were observed in this study, resulting in a high abundance (>100 in 10 min) for some sound types (types 14 and 22).

4.2 | Species-recognizable sound production

Three species of water beetle in the Dytiscidae, *A. sulcatus*, *H. ovatus*, and *R. suturalis* were shown to produce distinct and species-recognizable signals (Figure 6), demonstrating the potential for monitoring aquatic arthropods from audio recordings. In the pond studies, sound type 35 closely resembles that produced by the lesser-diving beetle (*A. sulcatus*), and was detected once in pond SABA, the same pond from which the *A. sulcatus* individual recorded in this study was collected. Although several studies have explored the morphological features of the stridulatory apparatus of dytiscids to supplement identification keys (Foster & Friday, 2011; Foster, Bilton & Friday, 2014), few studies have focused on the sounds that such apparatus produces. No recent studies have explored the acoustic characteristics or behavioural implications of the species recorded here. Furthermore, we are not aware of previous research that has characterized the stridulations produced by *H. ovatus* or *R. suturalis*, and so the stridulation characteristics described here are likely to be the first descriptions for these species. Smith (1973) noted the production of clicking sounds by *A. sulcatus* and attributed them to pre-flight activity. In addition, Desjonquères (2016) observed *A. sulcatus* making a low-frequency sound before leaving the recording aquaria and flying away, also attributing the sounds to pre-flight activity. No attempt to escape the field tank was made by the *A. sulcatus* individual in this study. During the second phase of the *A. sulcatus* signal, a 'humming' sound was produced. Laker (1879) and Arrow (1942) suggest that humming is used to deter predators by causing unpleasant vibrating sensations. The use of both

high-frequency clicks that dissipate quickly and low-frequency humming, which travels long distances, may be indicative of a behaviour that benefits both long-distance and short-distance reception. For example, a courtship signal of such a structure would benefit prospecting mates by providing precise information on the location of the source, while at the same time providing longer-range 'invitations'. However, it is widely accepted that dytiscids do not produce any kind of acoustic courtship behaviour (Bergsten, Töyrä & Nilsson, 2001; Bergsten & Miller, 2007), although this is known to occur in the Hydrophilidae (Wilson et al., 2015). Given this, it seems more likely that such signals are used for other forms of communication with conspecifics.

The high-frequency stridulations (5.2–12.5 kHz) produced by *H. ovatus* may be the result of an initial scrape of the stridulatory apparatus, and a second scrape as they reset. Such a system would maximize the likelihood of the signal being received by a conspecific while also conserving energy. Although there are no studies detailing the stridulations produced by *H. ovatus*, Young (1963) notes the presence of a stridulatory apparatus consisting of a ridge with striations on the anterior side of the hind coxae for the morphologically closely related species *Hyphydrus cuspidatus* and *Hyphydrus clypealis*.

Interestingly, *R. suturalis* may have produced stridulations that occur in both high-frequency and low-frequency bands, possibly a product of the simultaneous use of different stridulatory mechanisms. Two mechanisms of sound production have been proposed for *Rhantus* species: an interaction between the costal vein and the elytra (Reeker, 1891), and also between the axillary sclerites (Smith, 1973). Smith (1973) also noted the ability to stridulate in both *Rhantus gutticollis* and *Rhantus binotatu*. These species produced waterborne 'buzzing' stridulations, varying in duration and temporal patterning, that were subsequently followed by emigration from a habitat. However, no evidence was found here to suggest this behaviour for *R. suturalis*. It is also possible that the frequency gap observed here was the result of the hydrophone causing certain frequencies to resonate unexpectedly in the shallow water of the field tank (Aiken, 1982). Further work would be needed to resolve this question, however.

4.3 | Caveats and potential future application of ecoacoustics

The most significant limitation of this study is the 10-min survey period that is undoubtedly insufficient at capturing the temporal acoustic variation present in each study pond. Previous ecoacoustic research has reported diurnal variation in acoustic richness and activity across a variety of freshwater ecosystems (Decker et al., 2020; Gottesman et al., 2020; Karaconstantis et al., 2020; Linke, Gifford & Desjonquères, 2020). For an Australian river soundscape, Karaconstantis et al. (2020) showed that fishes were most acoustically active during the day and least active at dawn, whereas aquatic insects began stridulating at dusk and were most

acoustically active between midnight and dawn. After recording for 23 days in Cantarana Swamp, Costa Rica, Gottesman et al. (2020) concluded that 18 sound types produced by aquatic insects formed an active night chorus, a less active daytime soundscape, and short periods of silence at dawn and dusk. Although the survey presented here cannot claim to capture temporal acoustic variation, it does demonstrate the efficacy of a rapid acoustic survey approach that can be used to obtain preliminary data quickly while avoiding the major data-processing challenge associated with more substantial ecoacoustic surveys.

Despite clear differences between the soundscapes of restored open-canopy and unmanaged terrestrialized ponds reported in this study, acoustic signals, defined here as 'sound types', could not be attributed directly to the species that produced them, owing to the lack of an established audio reference library. Instead, a broad assessment of the relative sound diversity of each pond was made that can be reasonably assumed to provide an approximation of water beetle and water bug richness. We confidently suggest that sound type 35 is produced by the lesser-diving beetle (*A. sulcatus*), owing to its similarity with the recording of *A. sulcatus* captured in the field tank in this study. The tank used in this study to record water beetle sounds, however, was susceptible to background noise and was constructed from flat Perspex walls, which may have caused some sound waves to reverberate unnaturally. In future work, the recording of species-specific signals in a laboratory would reduce background noise, improve the clarity of recordings, and allow for the suitable acclimatization of individuals to the recording tank, thus minimizing the influence of stress. In addition, underwater video could be used to observe the behaviour of the specimens while stridulations are occurring, permitting more accurate and detailed ecological interpretations.

In this study sound-type diversity may well be an overestimate of species richness. It is likely that some sounds may have been incorrectly identified as originating from invertebrates, including background noise and sounds resulting from plant respiration (Felisberto et al., 2015). In addition, it is possible that multiple sound types may have been produced by a single species. However, given that many of the recorded signals differed conspicuously in amplitude and frequency, probably as a result of the varying physiological apparatus and stridulatory capabilities of the different water beetle and water bug species that made them, we are confident that the overall patterns identified in this study are correct. The questions raised by this study highlight the urgent need for extensive future work, as piloted here, aimed at building up sound reference libraries for aquatic invertebrates and other species groups.

Similar to eDNA-based work (Harper et al., 2019), this pilot study confirms that ecoacoustics has the potential to be used effectively alongside traditional sampling methods as a non-invasive approach for assessing aquatic plant and invertebrate communities, and hence conservation value and restoration success for ponds. However, further research, determining the origin of sound types, is required before detailed ecological conclusions can be drawn. In addition, although aquatic insects often produce most of the acoustic diversity

in ponds, ideally a broader perspective is required to make a comprehensive assessment of pond restoration success using underwater soundscapes (Aiken, 1985b). A passive ecoacoustic monitoring approach that considers the sounds produced by arthropods, amphibians, fishes, aquatic plants, and the decomposition of organic matter may offer much meaningful ecological information regarding pond conditions and quality, which is expensive to obtain using traditional survey approaches. Moreover, ecoacoustic surveys could be used to monitor ponds with a citizen science approach, affording considerable scope for effective public engagement. Schools, local environment action groups, landowners, and farmers could all participate in ecoacoustic surveys, providing a potentially powerful but hitherto little explored aural means of connecting people with the aquatic environment.

In the future, the continuous monitoring of soundscapes could be achieved by passive acoustic monitoring, in which one or multiple hydrophones are deployed in aquatic habitats (Linke et al., 2018), and this would allow the findings of the current study to be tested fully. It is clear, however, that pond soundscapes are packed with biological information, underlining the potential of ecoacoustic monitoring as a highly effective and engaging non-invasive freshwater monitoring tool.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest associated with this work.

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